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Journal of Power Sources 128 (2004) 231–238

JOURNAL OF POWER SOURCES

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Uniformity analysis at MEA and stack Levels for a Nexa PEM fuel cell system

Wenhua H. Zhu, Robert U. Payne, Donald R. Cahela, Bruce J. Tatarchuk*

Department of Chemical Engineering, The Center for Microfibrous Materials Manufacturing, Auburn University, Auburn, AL 36849, USA

Received 12 September 2003; accepted 30 September 2003

Abstract

The Nexa™ power module is evaluated at membrane-electrode-assembly (MEA) and stack levels. The I–V Curves of the Nexa™ PEM fuel cell system is measured using periodic current interruption to maintain isothermal stack temperature. The uniformity analysis is mainly performed on the load of 800 W for all MEAs in 10 individual Nexa™ stacks. Statistical data show that the MEA voltage without an external load averages 224 mV higher than that with a load of 800 W. The MEA voltage difference is especially pronounced around the two cells at the air compressor side. The average difference is 8.8% and the highest difference is 13.1% between the minimum MEA voltage in the stack and the mean value. This voltage difference reveals a possibility to increase the product power capability and cut the cost per kilowatts by improving the weak performance electrodes or MEAs in the stack.

Keywords: PEM fuel cells; System evaluation; Uniformity analysis

1. Introduction

The mobile, portable power systems consist of two major power categories, continuous power and pulse power. Fuel cells are being widely investigated and applied for various electronics and communication equipment [1]. During continuous operation, the proton exchange membrane (PEM) fuel cell stack has demonstrated good power capability but poor response for instantaneous power demands. It usually takes 2∼5 min to reach an acceptable operational condition because the polymer electrolyte membrane needs to be humidified for optimum performance. However, high power density, relatively quick start-up, rapid response to varying loads, and low operating temperature characteristics make the PEM fuel cells preferable for automobiles and other applications requiring high power density [2]. Fancesco et al. [3] discussed PEM fuel cell systems for a wide range of automotives and investigated the transient response to optimize the start-up using a PEM fuel cell stack model. Privette et al. [4] evaluated a ship service fuel cell (SSFC) system for power generation due to its high system level efficiency, few moving parts, little or no maintenance, and low acoustic and thermal signatures. There are many parameters that have effects on the PEM stack power output. The operational condition, MEA and stack features are related to the power output level. This paper describes efforts on uniformity analysis of Ballard Nexa™ stack at membrane-electrode-assembly (MEA) and stack levels.

2. Experimental

The BPS Nexa™ power module (Ballard Power Systems Inc.) is a small, low maintenance and fully automated fuel cell system designed to be integrated into products for portable and back-up power markets. The stack has a specified net output power of 1200 watts at full load with about 26 V. Hydrogen (>99.99%) and air are supplied to the sides of two gas channels formed in the flow field plates. The MEA of the Nexa™ stack consists of the anode and cathode separated by a polymer membrane electrolyte. Each of the electrodes is coated on one side with a thin platinum catalyst layer. A single fuel cell consists of an MEA and two flow field plates as shown in Fig. 1. The Nexa™ stack has a total of 47 MEAs or cells connected in series through 48 flow-field plates. The preferred operating temperature is 65 °C at 1200 W power output. Ten of the Nexa™ stacks from Ballard were examined and tested in this work. The Nexa™ stack and experimental hard wares are shown in Fig. 2. The supply pressures to the stack were 5.0 psig for the fuel and 2.2 psig for air oxidant. The operating pressure

* Corresponding author. Tel.: +1-334-844-2023.
E-mail address: brucet@eng.auburn.edu (B.J. Tatarchuk).

0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2003.09.074

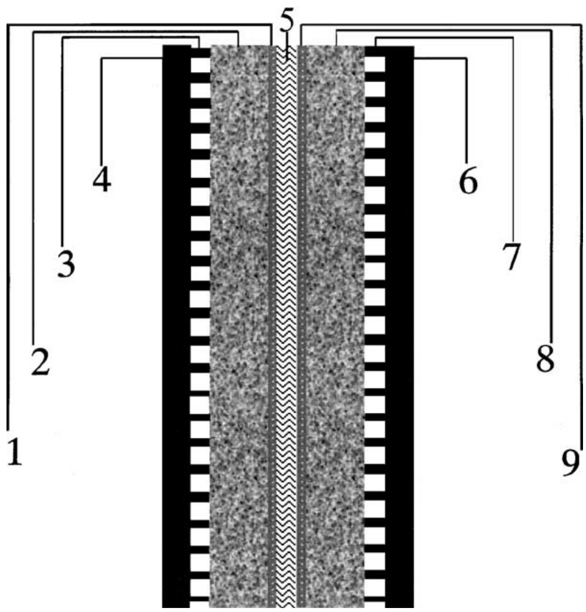

Fig. 1. Single fuel cell and membrane electrode assembly in the PEM fuel cell stack. 1, Oxidant catalyst layer (cathode); 2, oxidant diffusion layer; 3 and 4, oxidant flow field plate; 5, proton exchange membrane; 6 and 7, fuel flow field plate; 8, fuel diffusion layer; 9, hydrogen catalyst layer (anode); l, 2, 5, 8 and 9, membrane-electrode-assembly (MEA); and 1–9, single fuel cell unit.

at fuel supply inlet was chosen at 40 psig. The stack was air cooled and had no outside fuel and oxidant humidification. The only by-products of the reaction were water and heat.

Electric loads (RBL488 TDI Transistor Devices–Dynaload® Division and 6060B HP DC Electronic load), Micronta digital multimeters, and Ohmite heat sink power resistors were taken to do the evaluations on the Nexa^{TM} MEAs and stacks. The RBL488 single channel load is ideal for testing and analysis of fuel cells and batteries at high range current and constant power capabilities. The ultra-fast slew rate provides unmatched power supply transient testing capabilities. These features make the electric load a good solution for the fuel cell tests.

3. Results and discussion

3.1. Nexa^{TM} stack warm-up and cool-down

The PEM fuel cell stack has an essential checking sequence on MEA voltage, stack performance and operating conditions before the stack enters into its running state. The BPS Nexa^{TM} power module is usually started in less than 2 min. If any of the start-up criteria are not met during the staring period, the system fails and stops. The stack number is viewed the same as the Nexa^{TM} fuel cell serial number for convenient description. The NexaMon OEM software was employed for most Nexa^{TM} data monitoring. If all starting criteria were met, the Nexa^{TM} power module was able to run for start. The start-up parameters for the Nexa^{TM} system #881 were partially shown on Fig. 3. The stack voltage was maintained at about 40 V without an external load after successful start-up at room temperature.

Then the Nexa^{TM} power module was warmed up to a certain constant temperature at a specific load. The stack temperature only reached 32 °C in 10 min at a load of 5 A output current. The operation temperature was important for stack

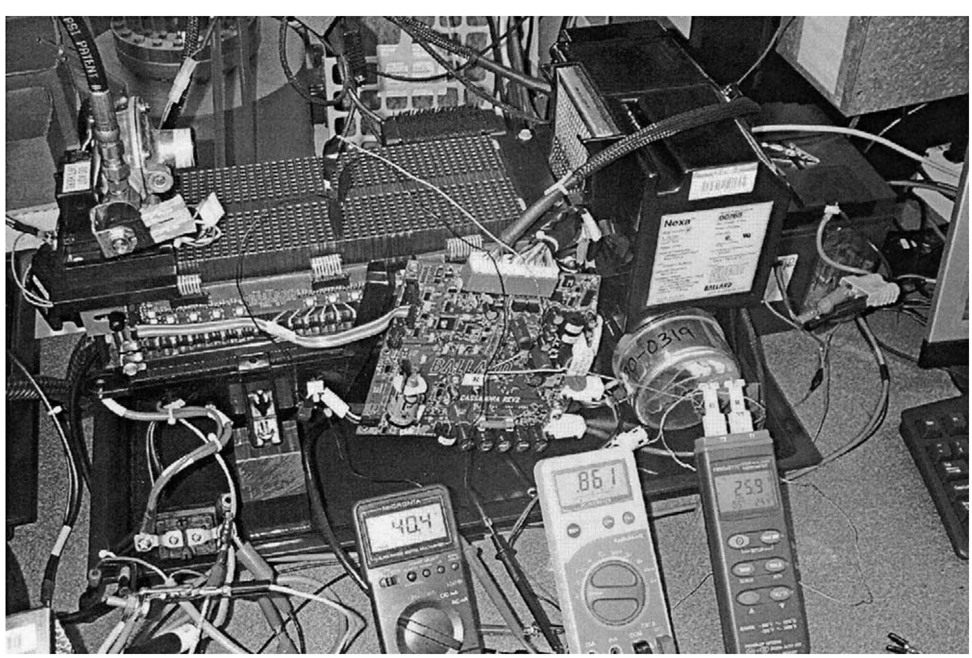

Fig. 2. Nexa^{TM} power module and experimental hardwares. Stack #768 voltage at 40.4 V and the 27th MEA's voltage at 0.861 V with no external load at room temperature.

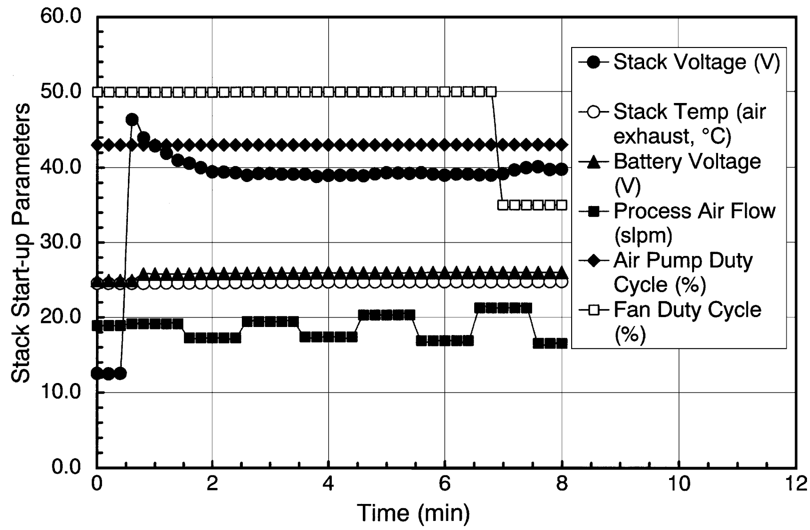

Fig. 3. Nexa^{TM} #881 start-up curves vs. operation time. Indoor air and compressed Grade-5 hydrogen supply.

peak power capability. In order to evaluate the time requirement for rapid stack warm-up, the stack #768 was operated at a load of 1.39 Ω for 1 min and then changed to a load of 0.68 Ω for the rest of operation period. Two different load levels were chosen for the stack here in order to reach 65 °C operating temperature for rapid stack warm-up. If this type of stack was well humidified, a higher power load (0.68 Ω) was applied to the stack #881. As shown in Fig. 4, two stacks (#768 and #881) at room temperature (25 °C) reach 60 °C in about 3 min and operate at 65 °C after 5 min. Once the stack finished its operation, it was cooled down close to room temperature in about 20 minutes with no external load (Fig. 5). This is an acceptable condition for the Nexa^{TM} power module to be shut off. As a whole, the Nexa^{TM} stack is able to be warmed up to 65 °C in 5 min for a 1200 W power output at 25 °C room temperature.

3.2. Stack polarization curves

The Nexa^{TM} power module has a maximum voltage of 50 V and provides 1200 W of unregulated DC power output. The ambient temperature at rated power is allowed from 3 °C to 30 °C. The Nexa^{TM} power module is a fully automated fuel cell system with low maintenance. It produces zero harmful emissions and permits indoor operations. The stack polarization curve provides significant parameters for power management and transient applications. The experimental polarization curve is slightly different between the positive and negative load increments because the produced water content is a function of load and the water content in membrane at equilibrium is time dependent. The small difference is neglected in the polarization curve experiments. However, the automated system is not permitted to operate

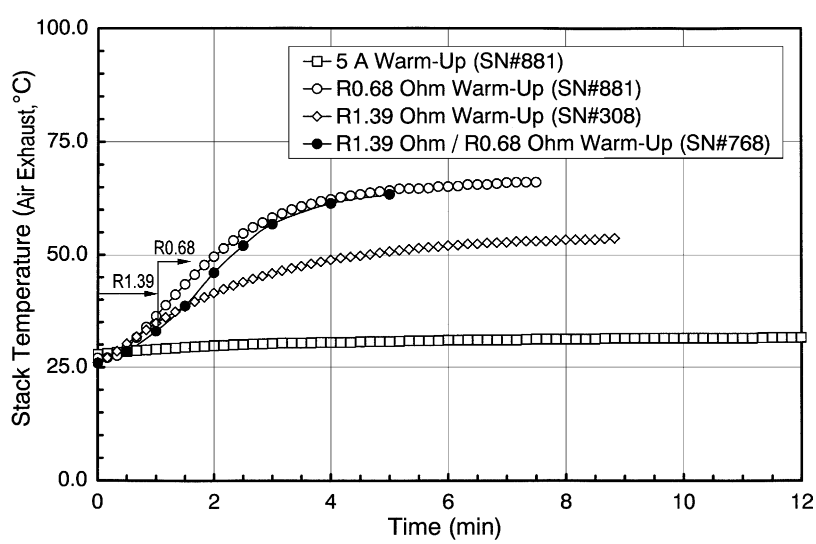

Fig. 4. Stack temperature vs. stack warm-up time. Indoor air and compressed Grade-5 hydrogen supply.

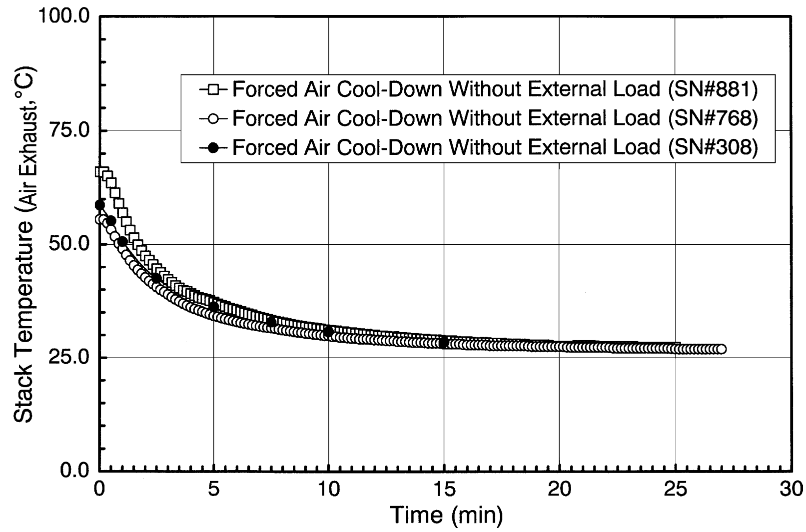

Fig. 5. Stack cool-down curves with no external load measured from BPS Nexa™ stacks.

at a fixed temperature if the load is changed. The I–V curves for BPS PEM fuel cell system were measured with periodic current interruption (PCI) to maintain isothermal stack temperature. In details, the stack voltage was recorded at a certain current and temperature. Then the current was quickly interrupted and the system load was adjusted back to maintain isothermal stack temperature. By using the PCI technique, the polarization curves for the power module, i.e. stack #751, are plotted at 24, 45, and 65 °C as shown in Fig. 6. The stack was not operated at a high current level and room temperature (24 °C) because the mass transfer problem and concentration polarization may reduce the lifetime of the power module. The stack power output was measured at 1131 W at 43.5 A and 45 °C, and 1283 W at 45.5 A and 65 °C (Fig. 7). Both of these are very close to the Ballard specific point. The calculated stack resistance drops from 1.2 to 0.1 Ω when the stack output current increases from 0.1 to 5 A. The stack resistance has no obvious difference at 45∼65 °C, especially at more than 10 A output current as shown in Fig. 7. The Nexa™ fuel cell system and stacks are able to work at high current levels. The uniformity and weakness analysis are important to the stack performance and its operation lifetime.

3.3. MEA and stack uniformity

Ten Nexa™ power modules were individually operated at an approximate 800 W power output level. The MEA voltage in the stack was then measured until the power module reached a steady state, i.e. constant fuel pressure and stack temperature (57 °C). The voltage of all 47 MEAs in 10 stacks was shown in Fig. 8. The MEA series order is started from

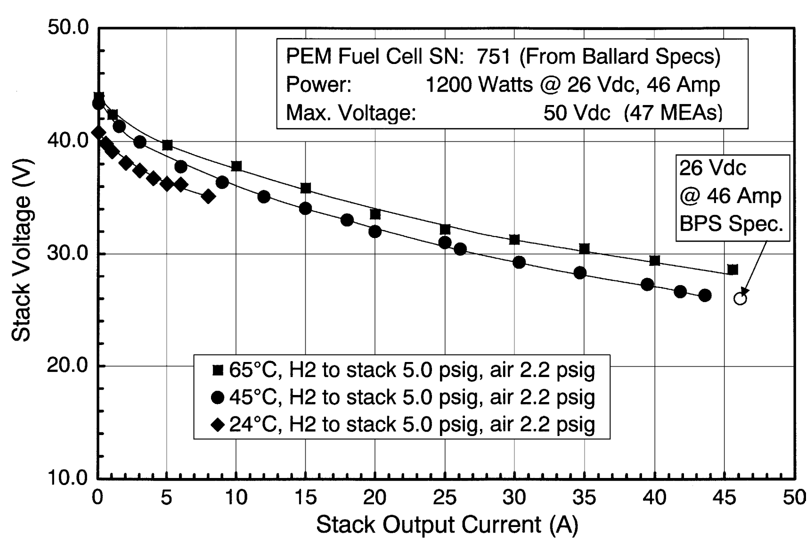

Fig. 6. Polarization curves measured from the BPS Nexa™ stack with periodic current interruption to maintain isothermal stack temperature.

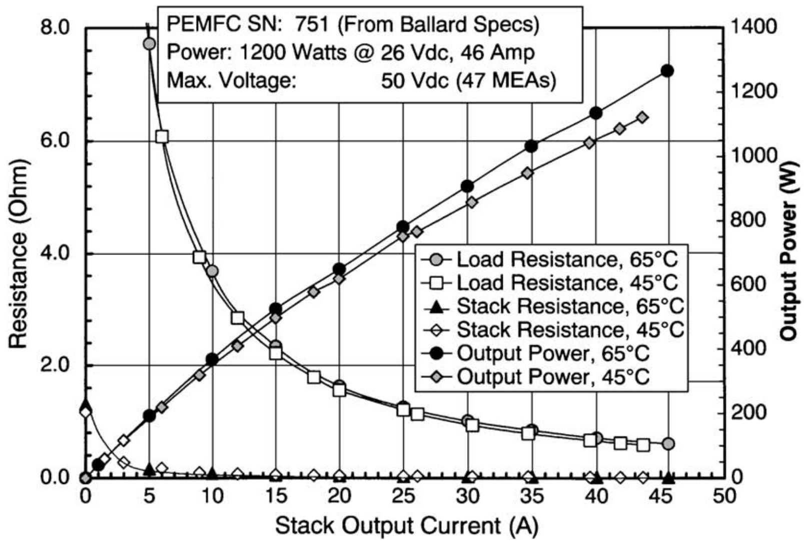

Fig. 7. Stack resistance and output power as a function of stack output current.

the hydrogen side to the compressed air side. Quite a few MEAs in different stacks have the same lower voltage at the 46th and the 47th cells. Average voltage of all the MEAs was 0.638 V at 800 W. And this voltage is 224 mV lower than that of stacks at no external load, which has an average voltage of 0.862 V. The voltage at no external load is somewhat lower than the normal open circuit voltage from 0.900 to 1.100 V. This is mainly decided by the different system design. Fig. 9 shows the voltage difference with an outside load and with no external load for the stack #308. Similarly, the MEAs in the stack #308 without an external load have a voltage of 0.870 V. But these MEAs have different voltage drops at 800 W loads. The difference between the MEA voltage is cause by electrode limited uniformity (catalyst distribution, electrode thickness, inner gas distribution etc.), MEA uniformity, and stack gas/liqilid distribution management. Especially noticeable is that the 46th and 47th cells have much larger voltage drops than the other cells. The lower voltages of these cells highly reduce the high power capability for the stack systems. This may be caused by gas distribution problem, water flooding, or low reaction temperature at the compressor side. It will be extensively examined and diagnosed with electrochemical inpedance spectroscopy.

3.4. MEA and stack statistic data analysis

For the individual Nexa™ stack, the statistical MEA data and the measured stack voltage were listed in Table 1. The second minimum and the second maximum voltage were also shown in the above table. The MEAs in the stack #792

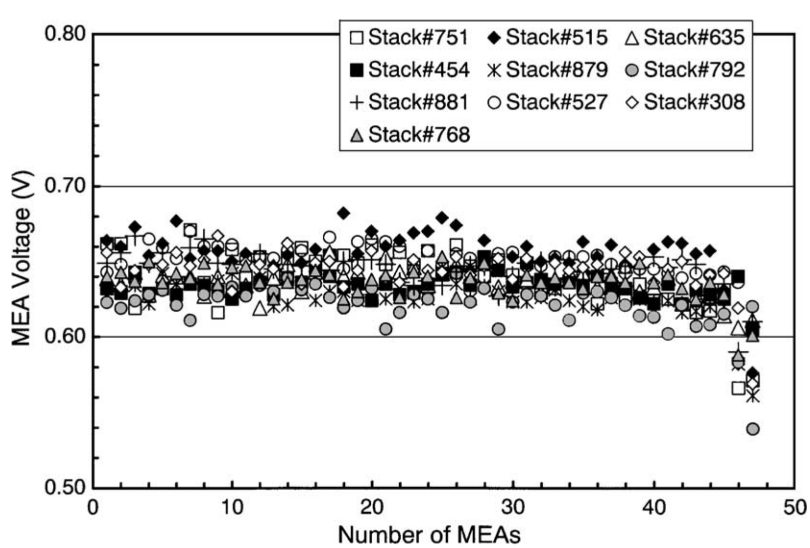

Fig. 8. Voltage of MEAs in series from hydrogen to oxygen side in 10 BPS Nexa™ stacks. Stack power output 800 W at 57 °C with indoor air and compressed Grade-5 hydrogen supply.

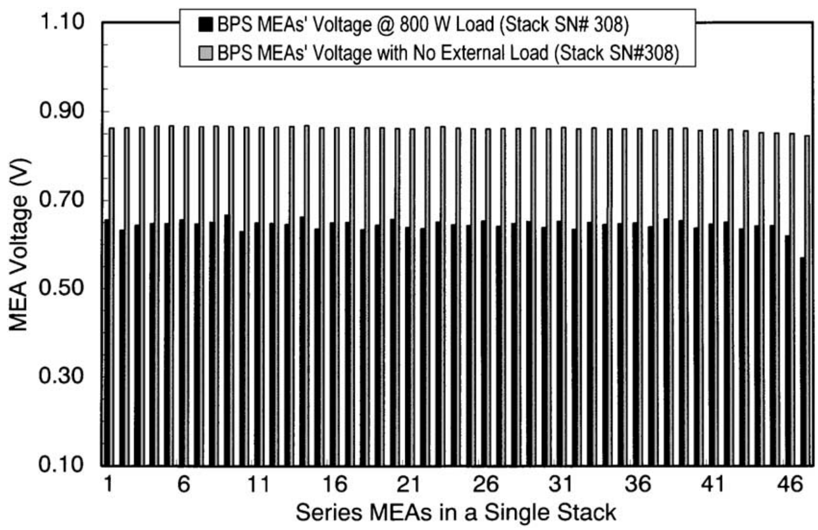

Fig. 9. Voltage of MEAs in series with/without a load in the Nexa^{TM} stack. Indoor air and compressed Grade-5 hydrogen supply.

has a lowest average voltage of 0.620 V and the MEAs in the stack #515 has a highest average voltage of 0.655 V. The difference of the MEA voltage sum between the two above stacks is 1.62 V and the difference of the measured stack voltage between two stacks is 1.44 V. The experimental statistical voltage is 30.20 ± 0.38 V for each Nexa^{TM} stack at 800 W power output. The voltage normal distribution is shown in Fig. 10. The exact shape of the normal distribution depends on the MEA voltage mean and the standard deviation of the distribution. The standard deviation is a measure of spread and indicates the amount of departure of the values from the voltage mean. Differences in standard deviation values model the shape of the voltage distribution. Although most of the distribution remains symmetric, the distribution becomes flatter if all MEA voltages of 10 stacks at load are put together. This increases the standard deviation, which corresponds to more diversity between the voltage observations. However, the Nexa^{TM} MEA voltage has a sharp shape without an external load, which means it has small standard deviation and no voltage difference at no external load.

According to statistical data in Table 1, the average difference is 8.8% and the highest difference is 13.1% between the minimum MEA voltage in the stack and the mean value. This difference reveals that it is possible to increase the product power level and cut the cost per kilowatts by improving the weak electrodes or MEAs in the stack. The voltage difference is mostly caused by electrode, MEA, and stack uniformity. This reminds that operation of stacks in series or parallel should take the voltage difference into consideration. High power capability stacks with similar voltage at load are preferred for series or parallel operation.

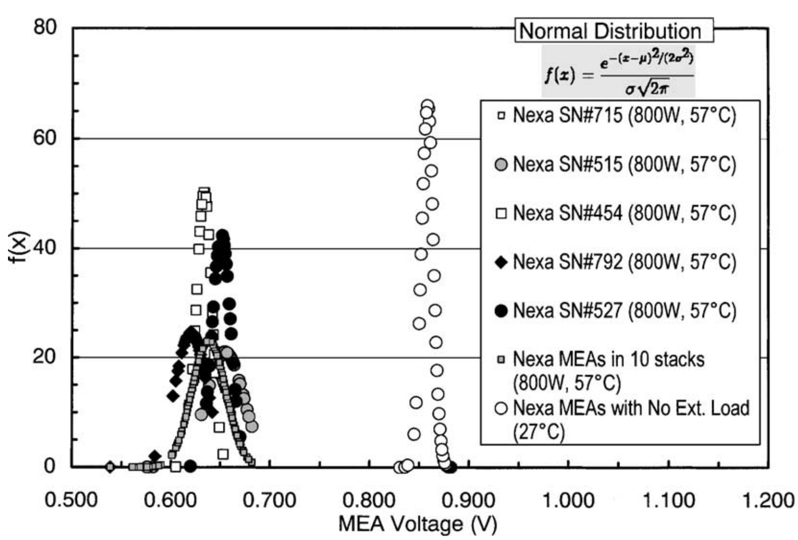

Fig. 10. Normal distribution curves at a stack power output 800 W and 57 °C with indoor air and compressed Grade-5 hydrogen supply.

Table 1
Data statistics and sample analysis of MEA voltage in 10 Nexa™ PEMFC power modules, individually measured at 800 W and 57 °C

Serial number	751	515	635	454	879	792	881	527	308	768
Mean	0.6377	0.6547	0.6363	0.6334	0.6257	0.6203	0.6445	0.6511	0.6437	0.6358
Standard error	0.0030	0.0028	0.0015	0.0012	0.0020	0.0024	0.0019	0.0014	0.0021	0.0017
Median	0.6400	0.6570	0.6390	0.6340	0.6260	0.6240	0.6470	0.6520	0.6460	0.6380
Mode	0.6400	0.6640	0.6430	0.6350	0.6300	0.6280	0.6490	0.6520	0.6440	0.6360
Standard deviation	0.0206	0.0190	0.0102	0.0079	0.0137	0.0162	0.0127	0.0094	0.0142	0.0114
Sample variance	0.0004	0.0004	0.0001	0.0001	0.0002	0.0003	0.0002	0.0001	0.0002	0.0001
Kurtosis	3.7925	9.9260	1.3641	2.9148	12.0925	13.4662	7.3851	1.3543	16.3477	6.9503
Skewness	−1.4933	−2.7319	−0.9486	−0.5390	−2.9227	−3.0417	−2.1169	−0.5627	−3.2389	−2.1206
Range	0.105	0.106	0.05	0.048	0.085	0.103	0.077	0.05	0.098	0.065
Minimum	0.566	0.576	0.606	0.605	0.561	0.539	0.590	0.620	0.569	0.588
Min2nd	0.571	0.582	0.611	0.622	0.582	0.584	0.610	0.636	0.619	0.601
Maxmum	0.671	0.682	0.656	0.653	0.646	0.642	0.667	0.670	0.667	0.653
Max2nd	0.662	0.679	0.653	0.649	0.642	0.639	0.665	0.666	0.662	0.650
Mean-Minimum	0.072	0.079	0.030	0.028	0.065	0.081	0.056	0.031	0.075	0.048
Count	47	47	47	47	47	47	47	47	47	47
MEA voltage, E_i (V)	0.638 ± 0.007	0.655 ± 0.006	0.636 ± 0.003	0.633 ± 0.003	0.626 ± 0.005	0.620 ± 0.005	0.645 ± 0.004	0.651 ± 0.003	0.644 ± 0.005	0.636 ± 0.004
Sum, statistic E_{stack} (V)	29.97	30.77	29.91	29.77	29.41	29.15	30.29	30.60	30.25	29.88
Stack voltage, E_{expt} (V)	30.32	30.76	29.86	29.96	29.66	29.32	30.57	30.95	30.47	30.09

Confidence level, 98%.

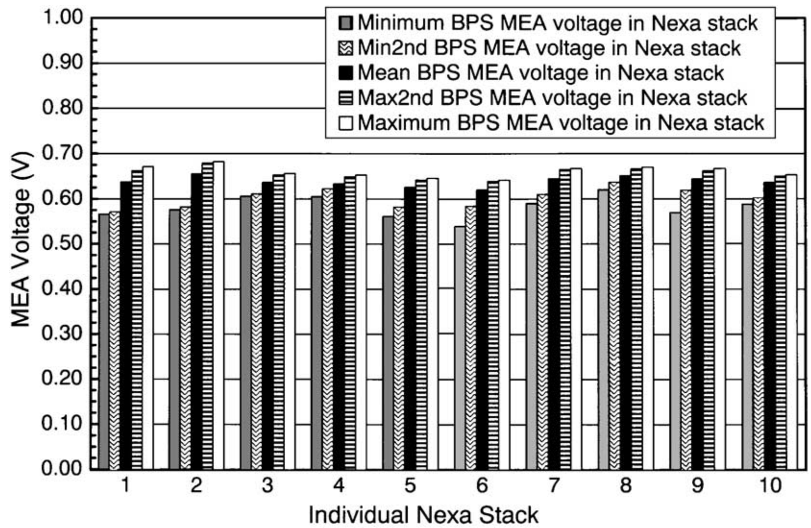

Fig. 11. Statistical MEA voltage data in 10 Nexa™ stacks. Stack power output 800 W at 57 °C with indoor air and compressed Grade-5 hydrogen supply.

The mean, maximum, and minimum data of the MEA voltage in 10 Nexa™ stacks are shown in Fig. 11. The stack numbers from left to right in Table 1 are shown as 1–10 in Fig. 11, respectively. The MEAs have an average voltage of 0.638 V in the stack #751(1). But the stack also has the minimum voltage of 0.566 V and the second minimum voltage of 0.571 V. If the above MEA performance is improved from the minimum voltage to the average level, the power capability is potentially increased by 11.3%. If a little more catalyst loading is applied to these electrodes with weak performance, or the gas distribution and purge system design are improved, the power module could potentially obtain a higher power output capability. This improvement prospectively reduces unit cost per kilowatts.

4. Conclusion

Uniformity analysis at MEA and stack levels has been conducted for the Nexa™ fuel cell system. The results of the MEAs and stack voltage at the load of 800 W reveal that difference exist among those MEAs at load in the same stack, especially the two cells at the air compressor side for the Nexa™ stack. The MEAs have an average voltage of 0.638 V in the stack #751. It also has the minimum voltage of 0.566 V. The improvement of the MEA performance from the minimum voltage to the average level potentially increases the stack power capability by 11.3%. This voltage difference reveals that it is possible to increase the product power capability and cut the cost per kilowatts by improving the weak performance electrodes or MEAs. This is likely realized by adding more catalysts to the electrodes, adjusting the gas distribution/purge system design, or changing with high-power-density MEAs in the stack.

Acknowledgements

This work was performed under a US Army contract at Auburn University (DASG 60-00-C-0070) administered through the US Army Space & Missile Defense Command. The authors also wish to acknowledge contributions from Dr. Ryan Nickell, Mr. Dwight Cahela, and Ms. Georgian Allison during the work phases of this project.

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